EDDY CURRENT THICKNESS MEASUREMENT OF THE ZINC LAYER ON GALVANIZED STEEL WIRES

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NORMALIZED IMPEDANCE DIAGRAM FOR A LONG COIL ENCIRCLING A GALVANIZED STEEL WIRE

By resolving Maxwell's Equations for the case of a long coil encircling a galvanized wire (fig.1), we can calculate the normalized impedance diagram. Later, during the experiments, we will directly use this diagram to find the thickness of the zinc layer. Before resolving Maxwell's Equations, a few words about the normalized impedance diagram in general. Figure 2 shows the normalized impedance diagram for the simple case of a long coil encircling a wire made out of a homogeneous conductive material of permeability μ_r and with a fill factor equal to one. A fill factor, $\eta = \frac{a^2}{c^2}$ (fig. 3), equal to one, means that there is no air between the coil and the wire.The x axis represents the normalized resistance

$$\frac{R_p - R_e}{\omega L_e} \tag{1}$$

where R_p is the real component of the impedance Z_p of the coil when there is a part inside the coil , R_e and ωL_e are respectively the real and the imaginary components of Z_e when the coil is empty.

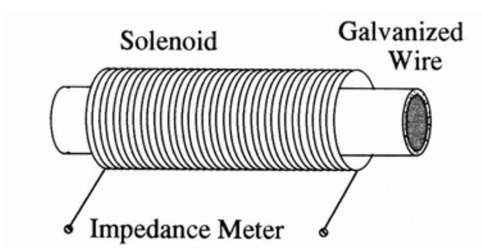

Fig. 1. Long encircling coil and galvanized wire.

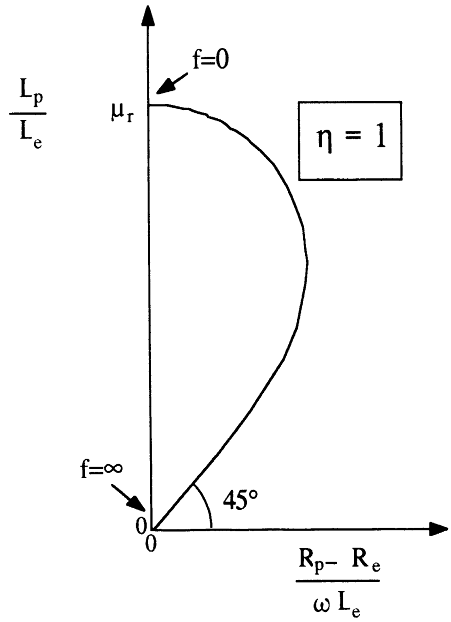

Fig. 2. Normalized impedance diagram for a normal wire.

The y axis represents the normalized inductance

$$\frac{\omega L_p}{\omega L_e} \tag{2}$$

where ωL_p is the imaginary component of Z_p when there is a part inside the coil. By dividing the impedance by ωL_e, we have normalized it. Thus the diagrams will not depend on the characteristics of the coil: i.e. number of turns , length and diameter if the coil is long enough. If we vary the test frequency from zero to infinity, we obtain the curve on the diagram, starting at point $(0, \mu_r)$ and ending in a straight line at 45° degrees at point (0,0). If the fill factor is not equal to one the curve would end at point $(0,1-\eta)$ [1]. Formulae 3 and 4 show that for the calculation of the normalized impedance diagram, we need to know the fluxes ϕ_p and ϕ_e crossing the coil respectively when there is a part inside the coil and when the coil is empty [2].

$$\frac{R_p - R_e}{\omega L_e} = -\text{imag}\,\frac{\phi_p}{\phi_e} \tag{3}$$

$$\frac{L_p}{L_e} = \text{real}\,\frac{\phi_p}{\phi_e} \tag{4}$$

$$\phi = \int \mathbf{B} dS = \mu \int \mathbf{H} dS \tag{5}$$

For the calculation of the fluxes, we will use the magnetization field H (formula 5). The magnetization field H inside an isotropic, continuous, conducting and non-hysteresic material is governed by a formula deduced from Maxwell's equations and Ohm's Law. This formula is

$$\text{curl curl } \mathbf{H} = -\sigma\,\mu\,\frac{\partial \mathbf{H}}{\partial t} \tag{6}$$

If we suppose the coil infinite long, the magnetization field H is then axial and formula 6 becomes (in cylindrical coordinates)

$$\frac{\partial^2 H}{\partial r^2} + \frac{1}{r}\frac{\partial H}{\partial r} - j\,k^2\,H = 0 \tag{7}$$

where j is the complex number and $k = \sqrt{\mu\sigma\omega}$ where μ is the permeability of the test piece, σ the conductivity of the test piece and $\omega = 2\pi f$ the pulsation of the eddy current. Figure 3 represents the galvanized wire with an outer radius a and a steel core with radius b. The galvanized wire is encircled by the coil with a radius c. If we want to calculate the total flux crossing the coil we must calculate the three magnetization fields: H_a (the field in the air between the coil and the wire), H_{zn} (the field in the zinc layer) and H_s (the field in the steel core). The field H_a is produced by the coil and is equal to $I_o\, e^{j\omega t}$ where I_o is the amplitude of the current circulating in the coil in amps / meters. H_{zn} is given by resolving equation 7 in the zinc layer and H_s is the solution to equation 7 solved in the steel core. The solutions are:

$$H_{zn} = \left(A\, J_o\left(\frac{k_{zn} r}{\sqrt{j}}\right) + B\, Y_o\left(\frac{k_{zn} r}{\sqrt{j}}\right)\right)\, e^{j\omega t} \tag{8}$$

$$H_s = C\, J_o\left(\frac{k_s r}{\sqrt{j}}\right)\quad e^{j\omega t} \tag{9}$$

J_o and Y_o are the Bessel functions of the first and second kind of order zero; k_{zn} and k_s are respectively equal to $\sqrt{\mu_o \sigma_{zn} \omega}$ and $\sqrt{\mu_o \mu_r \sigma_s \omega}$.

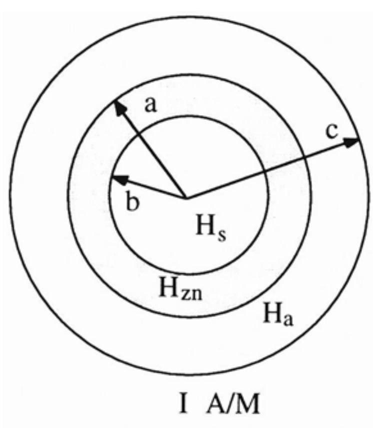

Fig. 3. Encircling coil and galvanized wire.

The three constants A, B, and C will be determined by the boundary conditions. We have three constants, so we need three boundary conditions. The first condition expresses the continuity of the field H at the surface of the wire:

$$H_a = H_{zn}(a) \qquad \text{or} \qquad A\, J_o\left(\frac{k_{zn}a}{\sqrt{j}}\right) + B\, Y_o\left(\frac{k_{zn}a}{\sqrt{j}}\right) = I_o \qquad (10)$$

The second condition expresses the same continuity but at the limit between the zinc layer and the steel core:

$$H_{zn}(b) = H_s(b) \quad \text{or}$$

$$A\, J_o\left(\frac{k_{zn}b}{\sqrt{j}}\right) + B\, Y_o\left(\frac{k_{zn}b}{\sqrt{j}}\right) = C\, J_o\left(\frac{k_s b}{\sqrt{j}}\right) \qquad (11)$$

And the third condition expresses the continuity of the electrical field E at the limit between the zinc layer and the steel core:

$$E_{zn}(b) = E_s(b) \quad \text{or}$$

$$\frac{k_{zn}}{\sigma_{zn}} A\, J_1\left(\frac{k_{zn}b}{\sqrt{j}}\right) + \frac{k_{zn}}{\sigma_{zn}} B\, Y_1\left(\frac{k_{zn}b}{\sqrt{j}}\right) = \frac{k_s}{\sigma_s} C\, J_1\left(\frac{k_s b}{\sqrt{j}}\right) \qquad (12)$$

J_1 and Y_1 are the Bessel functions of the first and second kind of order one.

With equations 10, 11 and 12 , we can calculate the values of A, B and C for every experimental case: e.g. low or high frequency, thick or thin zinc layer, ... When we know the value of the three constants we can compute the fluxes crossing the coil and thus we can draw our normalized impedance diagram. Formula 13 gives the expression of the ratio $\frac{\phi_p}{\phi_e}$ for a fill factor equal to one,

$$\frac{\phi_p}{\phi_e} = +\frac{2}{\alpha}\left[\, A\, J_1(\alpha) + B\, Y_1(\alpha)\right] - 2\,\frac{b}{a}\,\frac{1}{\alpha}\left[\, A\, J_1(\beta) + B\, Y_1(\beta)\right]$$

$$+ 2\mu_r\left(\frac{b}{a}\right)^2 \frac{1}{\gamma}\, C\, J_1(\gamma) \qquad (13)$$

with

$$\alpha = \left(\frac{k_{zn}a}{\sqrt{j}}\right) \qquad \beta = \left(\frac{k_{zn}b}{\sqrt{j}}\right) \qquad \gamma = \left(\frac{k_s b}{\sqrt{j}}\right)$$

Figure 4 shows the normalized impedance diagram for three wires: a steel core of radius 1 mm and a relative permeability of 70, a galvanized wire with the same steel core and a 10 µm zinc layer and the last with 100 µm layer zinc.We can see that the change of impedance between the steel core and the galvanized wire is important, even for a small layer of 10 µm. We will use this difference in our experiments. To establish this diagram we had to know diameter 2c of the solenoid, diameter 2a of the wire, diameter 2b of the steel core, the conductivity σ_{zn} of zinc as well as the conductivity σ_s and permeability μ_r of the steel core.

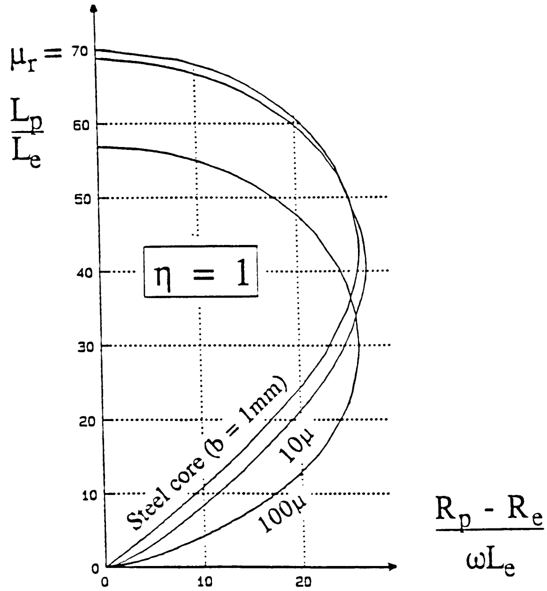

Fig. 4. Normalized impedance diagram for a steel core and two galvanized wires with the same steel core.

EXPERIMENTS

To verify the accuracy of our theoretical approach, we carried out experiments on electro-galvanized wires in which the diameter of the wire core is 2.2 mm. The wires core is identical for all the wires tried. Thus, we could calculate the impedance diagram relative to these electro-galvanized wires by determining the value of the conductivity σ_{zn} of zinc and the values of the permeability μ_r and the conductivity σ_s of steel.These are the parameters of the model. They were chosen to optimize the concordance between the theory and the experiment. The thickness of the zinc layer was determined by the double weighing method, weighing the galvanized wire on the one hand and the steel core on the other hand after chemically dissolving the zinc layer.Table 1 represents the results after optimization of the model by the best choice of σ_{zn}, σ_s and μ_r. The calculated thicknesses presented in the table were determined by the curve of the standardized impedance diagram to which the experimental point belongs. If we know σ_{zn}, σ_s, μ_r at each point of the standardized impedance diagram established for η=1, we can make a zinc thickness correspond.

Table 1. Experimental results obtained at a frequency of 1 MHz.

Steel Core Diameter mm	Real Thickness µm	Calculated Thickness µm	Error µm
2.2	11.4	11.51	-0.11
2.2	12.5	12.42	+0.08
2.2	13.9	13.93	-0.03
2.2	17.6	17.57	+0.03
2.2	21.1	21.19	-0.09

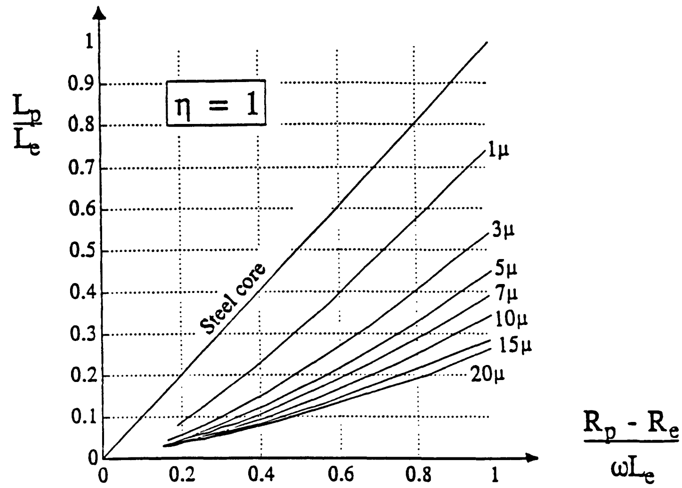

Fig. 5. Normalized impedance diagram used to find the thickness of the zinc layer, (high frequency zone of the diagram).

Table 2. Experimental results obtained at a frequency of 400 kHz.

Steel Core Diameter mm	Real Thickness µm	Calculated Thickness µm	Error µm
2.2	24.0	24.33	-0.33
2.2	26.5	27.59	-1.09
2.2	29.8	31.30	-0.50
2.2	32.3	33.23	-0.93
2.2	36.0	35.81	+0.19
2.2	38.8	39.67	-0.87
2.2	46.2	47.58	-1.38
2.2	52.7	52.75	-0.05
2.2	58.6	58.45	+0.15
2.2	64.7	64.73	-0.03

We can see that for both tables the errors are very small. One of the reasons for these good results is the fact that the steel core is identical for all the wires. Another reason is that the zinc layer is very homogeneous and constant on the wire, because of the electrical deposition, which brings the wires close to the theoretical hypotheses.

CONCLUSIONS

The method that we have followed consists of finding the exact solution to the problem using the Maxwell equations and then carrying out experiments staying as close as possible to the hypotheses taken to make the theoretical calculation, such as an infinitely long solenoid, a sheet of current, the homogeneity of zinc and steel.Other than knowing the exact diameter 2a of the product, we must know the conductivity σ_{zn} of the zinc as well as the conductivity σ_s and the permeability μ_r of the steel core to determine the thickness of the zinc layer for the equations of the model. This poses a problem for the industrial application of this measuring procedure. Research is being done to overcome this difficulty, for example by the concomitant determination of these parameters by multifrequency measurement.

REFERENCES

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